Tropical Cyclone Intensity Analysis and Forecasting

Mark DeMaria
National Hurricane Center

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Outline

- Estimating the Current Intensity (with Exercise)
- Factors that Influence Intensity Change
- Intensity Forecasting Models
- Official Intensity Forecasts
- Intensity Forecast Exercise
How Do We Estimate Intensity?

- **Satellites (primary)**
  - Geostationary infrared & visible images (Dvorak Technique)
  - Microwave soundings (AMSU)
  - Scatterometer derived surface winds (ASCAT)

- **Surface observations**
  - Ships, buoys, land stations (limited)
How Do We Estimate Intensity?

- Aircraft reconnaissance
- Flight-level winds
- GPS dropsondes
- Stepped-Frequency Microwave Radiometer (SFMR)
- Doppler radar
- Land-based (WSR-88D)
- Airborne
Exercise 1: Estimating the Current Intensity of Hurricane Bill

19 August 1800 UTC

Dvorak classification:

TAFB: T6.5 = 127 kt
SAB: T6.0 = 115 kt

3-hour average ADT: T6.4 = 125 kt
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Vortex Message

A) Date/Time of center fix
B) Center position
C) Std surface/min height
D) Max sfc wind (visually observed or SFMR)
E) Bearing/range of (D) from center
F) Max flt-lvl wind on inbound leg
G) Bearing/range of (F)
H) Minimum pressure
I) Max flt-lvl temp outside eyewall/PA
J) Max flt-lvl temp inside eye/PA
K) DPT/SST at (J)
L) Eyewall character (e.g., CLOSED)
M) Eye diameter (nm)
N) Method of fix
O) Fix accuracy (NAV/MET)
P) Remarks (includes outbound max)

000
URNT12 KNHC 191819 CCA
VORTEX DATA MESSAGE  AL032009
A. 19/17:57:30Z
B. 19 deg 16 min N
056 deg 55 min W
C. 700 mb 2665 m
D. 102 kt
E. 056 deg 24 nm
F. 134 deg 135 kt
G. 055 deg 27 nm
H. 947 mb
I. 11 C / 3045 m
J. 19 C / 3047 m
K. 6 C / NA
L. OPEN SW
M. C32
N. 12345 / 07
O. 0.02 / 0.5 nm
P. AF303 0203A BILL

SFMR surface wind

90% from 700 mb
Surface estimate = 0.9 × 135 kt = 122 kt

MAX FL WIND 135 KT NE QUAD 17:48:30Z

OB 12 CO
Dropsonde

MBL Wind
(average of lowest 500 m)

WL150 Wind
(average of lowest 150 mb)

Surface Wind
Northeast eyewall:

Surface = 122 kt (gust?)

MBL (lowest 500 m) = 

\[ 139 \times 0.8 = 111 \text{ kt} \]

WL150 (lowest 150 mb) = 

\[ 134 \times 0.83 = 111 \text{ kt} \]
Determine the Official Intensity

- Subjective Dvorak: 127 / 115 kt
- Objective ADT: 125 kt
- SFMR surface wind: 102 kt
- Recon sfc-adjusted flight-level wind: 122 kt
- Dropsonde surface value: 122 kt
- Drop sfc-adjusted WL150: 111 kt
- Drop sfc-adjusted MBL: 111 kt

- OFCL at 1800 UTC: 115 kt

We can only sample a part of the TC. Each observation has strengths and weaknesses. We want a value that is representative of the TC’s circulation.
EXERCISE 1
Intensity Estimation
Factors Affecting Tropical Cyclone Intensity

- Sea surface temperature (SST) / upper ocean heat content (OHC)
- Environmental winds, esp. vertical wind shear
- Trough interactions
- Temperature and moisture patterns in the storm environment
- Internal effects (e.g. eyewall replacement cycles)
- Interaction with land
Ocean Heat Content estimates the amount of heat available over a depth of warm water.

the greater the depth the more available heat that can be potentially converted to energy

Sea Surface Temperatures only provides a view of the very top layer of the ocean.
Vertical cross-section of PV (purple) and temperature anomaly from the GFDL model for the initialization of the 0000 UTC forecast on September 29
Vertical cross-section of PV (purple) and temperature anomaly from the 36-hour forecast GFDL model for the initialization of the 0000 UTC forecast on September 29.
Hurricane-Trough Interaction

Hurricane Bertha (1996)

12 July 1995 06 UTC

12 July 1995 12 UTC

12 July 1995 18 UTC
Getting Dry Air into the TC Circulation

Saharan Air Layer
How Moisture Affects Stability

LCL and LFC

Moist Tropical

SAL

Mid-Lat
In addition to large-scale environmental influences, tropical cyclone intensity change can be caused by inner-core processes, such as eyewall replacement cycles:

In stronger hurricanes, we often see a concentric eyewall develop at a larger distance from the center than the radius of the original eyewall.

When this outer eyewall becomes dominant, some weakening usually occurs.

However, this outer eyewall could contract, in which case the hurricane would re-intensify.
Hurricane Matthew Radar Loop
Hurricane Matthew Maximum Wind

![Graph showing wind speed over time](image-url)
In general, winds weaken over land due to lack of latent heating and increased friction.

Strong winds move inland farther if the TC is moving faster.

Terrain can cause significant local “speed-ups” (sometimes by more than 10 – 30%) over hills, valleys, etc.

Higher elevations in mountainous areas can have stronger winds than at sea level – common on Caribbean islands.
Weather Forecast Methods

• Classical Statistical Models
  – Use observable parameters to statistical predict future evolution

• Numerical Weather Prediction (NWP)
  – Physically based forecast models

• Statistical-Dynamical Models
  – Use NWP forecasts and other input for statistical prediction of desired variables
    • Station surface temperature, precipitation, hurricane intensity changes

\(^1\text{From Wilks (2006) and Kalnay (2003)}\)
Tropical Cyclone Intensity Forecast Models

• Statistical Models:
  – Decay SHIFOR (Statistical Hurricane Intensity FORecast with inland decay).
    • Based on historical information - climatology and persistence (uses CLIPER track).
    • Baseline for skill of intensity forecasts
  – Trajectory CLIPER
    • Statistically estimate track and intensity tendency instead of change over fixed time
      – e.g., $dV/dt$ instead of $V(t)-V(0)$

• Statistical-Dynamical Models:
  – SHIPS and DSHIPS (Statistical Hurricane Intensity Prediction Scheme):
    • Based on climatology, persistence, and statistical relationships to current and forecast environmental conditions (with inland decay applied in DSHIPS)
  – LGEM (Logistic Growth Equation Model):
    • Uses same inputs as SHIPS, but environmental conditions are variable over the length of the forecast (SHIPS averages over the entire forecast)
    • More sensitive to environmental changes

• Dynamical Models:
  – HWRF, HMON, COAMPS-TC, GFS, UKMET, NOGAPS, ECMWF
Overview of the SHIPS Model

• Multiple linear regression
  \[ y = a_0 + a_1 x_1 + ... a_N x_N \]
  • \( y \) = intensity change at given forecast time
  \( -(V_6 - V_0), (V_{12} - V_0), ..., (V_{120} - V_0) \)
  • \( x_i \) = predictors of intensity change
  • \( a_i \) = regression coefficients

• Different coefficients for each forecast time
• Predictors \( x_i \) averaged over forecast period
• \( x, y \) normalized by subtracting sample mean, dividing by standard deviation
SHIPS Predictors

1. Climatology (days from peak)
2. $V_0$ ($V_{\text{max}}$ at $t=0$ hr)
3. Persistence ($V_0-V_{-12}$)
4. $V_0 \times \text{Per}$
5. Zonal storm motion
6. Steering layer pressure
7. %IR pixels < -20°C
8. IR pixel standard deviation
9. Max Potential Intensity – $V_0$
10. Square of No. 9
11. Ocean heat content
12. $T$ at 200 hPa
13. $T$ at 250 hPa
14. RH (700-500 hPa)
15. $\theta_e$ of sfc parcel - $\theta_e$ of env
16. 850-200 hPa env shear
17. Shear $\times V_0$
18. Shear direction
19. Shear $\times \sin(\text{lat})$
20. Shear from other levels
21. 0-1000 km 850 hPa vorticity
22. 0-1000 km 200 hPa divergence
23. GFS vortex tendency
24. Low-level $T$ advection
25. GFS vortex warm core
SHIPS Regression Coefficients at 24 and 96 hr

- POT = Potential Intensity – Vmax(0)
- SHDC = 200-850 hPa Shear
- VSHR = Vmax*SHDC
- LHRD = SHDC*sin(lat)
- TWAT = GFS Vortex
- PER = Persistence
- 24 hr
- 96 hr
Impact of Land

- Detect when forecast track crosses land
- Replace multiple regression prediction with
  \[ \frac{dV}{dt} = - \mu (V - V_b) \]
  \[ \mu = \text{climatological decay rate} \approx 1/10 \text{ hr}^{-1} \]
  \[ V_b = \text{background intensity over land} \]
- Decay rate reduced if area within 1 deg lat is partially over water
Example of Land Effect

![Graph showing the decay of maximum wind (kt) over time (hr). The graph compares SHIPS and Decay-SHIPS.]
Limitations of SHIPS

• V predictions can be negative
• Most predictors averaged over entire forecast period
  – Slow response to changing synoptic environment
• Strong cyclones that move over land and back over water can have low bias
• Logistic Growth Equation Model (LGEM) relaxes these assumptions
Operational LGEM Intensity Model

\[
d\frac{V}{dt} = \kappa V - \beta (V/V_{mpi})^n V
\]

(A) \hspace{1cm} (B)

\[V_{mpi} = \text{Maximum Potential Intensity estimate}\]

\[\kappa = \text{Max wind growth rate (from SHIPS predictors)}\]

\[\beta, n = \text{empirical constants} = 1/24 \text{ hr, } 2.5\]

Steady State Solution: \[V_s = V_{mpi} (\beta/\kappa)^{1/n}\]
LGEM versus SHIPS

• Advantages
  – Prediction equation bounds the solution between 0 and $V_{mpi}$
  – Time evolution of predictors (Shear, etc) better accounted for
  – Movement between water and land handled better because of time stepping

• Disadvantages
  – Model fitting more involved
  – Inclusion of persistence more difficult
LGEM Improvement over SHIPS
AL and EP/CP Operational Runs 2006-2016
SHIPS Diagnostic File

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Available in real time from ftp://ftp.nhc.noaa.gov/atcf/stext
SHIPS Forecasts For East Pacific Hurricane Georgette (2016)

SHIPS forecasts often miss peak intensity during rapid intensification periods.
The Rapid Intensification Index

• Define RI as 30 kt or greater intensity increase in 24 hr
• Find subset of SHIPS predictors that separate RI and non-RI cases
• Use training sample to convert discriminant function value to a probability of RI
• AL and EP/CP versions include more thresholds (25, 30, 35, 40 kt changes, etc)
Linear Discriminant Analysis

• 2 class example
  – Objectively determine which of two classes a data sample belongs to
    • Rapid intensifier or non-rapid intensifier
  – Predictors for each data sample provide input to the classification

• Discriminant function (DF) linearly weights the inputs
  \[ DF = a_0 + a_1 x_1 + \ldots + a_N x_N \]

• Weights chosen to maximize separation of the classes
Graphical Interpretation of the Discriminant Function

DF chosen to best separate red and blue points
RII Discriminators

1. Previous 12 h max wind change (persistence)
2. Maximum Potential Intensity – Current intensity
3. Oceanic Heat Content
4. 200-850 hPa shear magnitude (0-500 km)
5. 200 hPa divergence (0-1000 km)
6. 850-700 hPa relative humidity (200-800 km)
7. 850 hPa tangential wind (0-500 km)
8. IR pixels colder than -30°C
9. Azimuthal standard deviation of IR brightness temperature
**Rapid Intensification**

**Hurricane Rick (2009 - East Pacific)**

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<th>Longitude</th>
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<td>72HR VT</td>
<td>19/1800Z</td>
<td>16.5N</td>
<td>111.5W</td>
<td>120 KT</td>
</tr>
<tr>
<td>96HR VT</td>
<td>20/1800Z</td>
<td>18.5N</td>
<td>113.0W</td>
<td>105 KT</td>
</tr>
<tr>
<td>120HR VT</td>
<td>21/1800Z</td>
<td>20.5N</td>
<td>113.0W</td>
<td>85 KT</td>
</tr>
</tbody>
</table>

*24 hrs*
## RI Guidance

### Hurricane Rick (2009 - East Pacific)

**EAST PACIFIC SHIPS INTENSITY FORECAST**

**GOES DATA AVAILABLE**

**OHC DATA AVAILABLE**

**RICK** EP202009 10/16/09 18 UTC

<table>
<thead>
<tr>
<th>TIME (HR)</th>
<th>0</th>
<th>6</th>
<th>12</th>
<th>18</th>
<th>24</th>
<th>36</th>
<th>48</th>
<th>60</th>
<th>72</th>
<th>84</th>
<th>96</th>
<th>108</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>V (KT) NO LAND</td>
<td>70</td>
<td>79</td>
<td>86</td>
<td>92</td>
<td>97</td>
<td>104</td>
<td>108</td>
<td>111</td>
<td>111</td>
<td>107</td>
<td>107</td>
<td>101</td>
<td>93</td>
</tr>
<tr>
<td>V (KT) LAND</td>
<td>70</td>
<td>79</td>
<td>86</td>
<td>92</td>
<td>97</td>
<td>104</td>
<td>108</td>
<td>111</td>
<td>111</td>
<td>107</td>
<td>107</td>
<td>101</td>
<td>93</td>
</tr>
<tr>
<td>V (KT) LGE mod</td>
<td>70</td>
<td>79</td>
<td>86</td>
<td>92</td>
<td>96</td>
<td>99</td>
<td>95</td>
<td>91</td>
<td>87</td>
<td>85</td>
<td>83</td>
<td>80</td>
<td>76</td>
</tr>
</tbody>
</table>

**2009 E. Pacific RI INDEX EP202009 RICK** 10/16/09 18 UTC

12 HR PERSISTENCE (KT): 20.0 Range: -20.0 to 35.0 Scaled/Wgted Val: 0.7/1.6
850-200 MB SHEAR (KT): 6.0 Range: 15.2 to 1.6 Scaled/Wgted Val: 0.7/0.3
D200 (10**7s^{-1}): 70.0 Range: -10.0 to 129.0 Scaled/Wgted Val: 0.3/0.4
POT = MPI-VMAX (KT): 96.7 Range: 46.6 to 134.3 Scaled/Wgted Val: 0.6/0.6
850-700 MB REL HUM (%): 79.4 Range: 64.0 to 88.0 Scaled/Wgted Val: 0.6/0.2
% area w/pixels <-30 C: 98.0 Range: 26.0 to 100.0 Scaled/Wgted Val: 1.0/0.5
STD DEV OF IR BR TEMP: 8.3 Range: 35.4 to 2.7 Scaled/Wgted Val: 0.8/1.3
Heat content (KJ/cm²): 46.8 Range: 4.0 to 67.0 Scaled/Wgted Val: 0.7/0.4

Prob of RI for 25 kt RI threshold= 78% is 6.8 times the sample mean(11.5%)
Prob of RI for 30 kt RI threshold= 71% is 9.3 times the sample mean( 7.7%)
Prob of RI for 35 kt RI threshold= 66% is 12.6 times the sample mean( 5.2%)
** RII Guidance Output **
Part of SHIPS diagnostic file

CURRENT MAX WIND (KT): 50. LAT, LON: 25.5 87.1

** 2015 ATLANTIC RI INDEX AL092016 HERMINE 09/01/16 00 UTC **
(SHIPS–RII PREDICTOR TABLE for 30 KT OR MORE MAXIMUM WIND INCREASE IN NEXT 24-h)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Value</th>
<th>RI Predictor</th>
<th>Range</th>
<th>Scaled Value(0-1)</th>
<th>% Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 HR PERSISTENCE (KT)</td>
<td>10.0</td>
<td>-49.5 to 33.0</td>
<td></td>
<td>0.72</td>
<td>4.6</td>
</tr>
<tr>
<td>850–200 MB SHEAR (KT)</td>
<td>11.9</td>
<td>28.8 to 2.9</td>
<td></td>
<td>0.65</td>
<td>1.9</td>
</tr>
<tr>
<td>HEAT CONTENT (KJ/cm2)</td>
<td>37.6</td>
<td>0.0 to 155.1</td>
<td></td>
<td>0.24</td>
<td>0.5</td>
</tr>
<tr>
<td>STD DEV OF IR BR TEMP</td>
<td>23.8</td>
<td>37.5 to 2.9</td>
<td></td>
<td>0.40</td>
<td>1.1</td>
</tr>
<tr>
<td>2nd PC OF IR BR TEMP</td>
<td>0.4</td>
<td>2.8 to -3.1</td>
<td></td>
<td>0.41</td>
<td>1.1</td>
</tr>
<tr>
<td>MAXIMUM WIND (kt)</td>
<td>50.0</td>
<td>22.5 to 121.0</td>
<td></td>
<td>0.78</td>
<td>0.8</td>
</tr>
<tr>
<td>D200 (10**7s−1)</td>
<td>47.2</td>
<td>-23.1 to 181.5</td>
<td></td>
<td>0.34</td>
<td>0.4</td>
</tr>
<tr>
<td>POT = MPI–VMAX (KT)</td>
<td>104.0</td>
<td>28.4 to 139.1</td>
<td></td>
<td>0.68</td>
<td>1.1</td>
</tr>
<tr>
<td>% AREA WITH TPW &lt;45 mm</td>
<td>0.0</td>
<td>100.0 to 0.0</td>
<td></td>
<td>1.00</td>
<td>0.7</td>
</tr>
<tr>
<td>BL DRY-AIR FLUX (w/m2)</td>
<td>143.4</td>
<td>960.3 to -67.1</td>
<td></td>
<td>0.80</td>
<td>0.0</td>
</tr>
</tbody>
</table>

SHIPS Prob RI for 20kt/ 12hr RI threshold= 7% is 1.3 times sample mean (5.5%)
SHIPS Prob RI for 25kt/ 24hr RI threshold= 24% is 2.1 times sample mean (11.6%)
SHIPS Prob RI for 30kt/ 24hr RI threshold= 12% is 1.7 times sample mean (7.2%)
SHIPS Prob RI for 35kt/ 24hr RI threshold= 11% is 2.7 times sample mean (4.2%)
SHIPS Prob RI for 40kt/ 24hr RI threshold= 8% is 2.9 times sample mean (2.8%)
SHIPS Prob RI for 45kt/ 36hr RI threshold= 10% is 2.1 times sample mean (4.9%)
SHIPS Prob RI for 55kt/ 48hr RI threshold= 19% is 3.7 times sample mean (5.1%)

Matrix of RI probabilities

<table>
<thead>
<tr>
<th>RI (kt / h)</th>
<th>20/12</th>
<th>25/24</th>
<th>30/24</th>
<th>35/24</th>
<th>40/24</th>
<th>45/36</th>
<th>55/48</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHIPS–RII</td>
<td>7.3%</td>
<td>24.1%</td>
<td>12.2%</td>
<td>11.4%</td>
<td>8.2%</td>
<td>10.4%</td>
<td>18.8%</td>
</tr>
<tr>
<td>Logistic</td>
<td>6.9%</td>
<td>28.6%</td>
<td>16.2%</td>
<td>8.6%</td>
<td>0.0%</td>
<td>8.5%</td>
<td>6.9%</td>
</tr>
<tr>
<td>Bayesian</td>
<td>3.1%</td>
<td>2.1%</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>0.6%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Consensus</td>
<td>5.8%</td>
<td>18.3%</td>
<td>9.6%</td>
<td>6.8%</td>
<td>2.8%</td>
<td>6.5%</td>
<td>8.8%</td>
</tr>
</tbody>
</table>
PATRICIA INTENSIFIED FROM 40 KT TO 185 KT IN 48 HOURS!

21 OCT 2015 12 UTC

23 OCT 2015 12 UTC
Tropical Cyclone Intensity Dynamical Forecast Models

- HWRF, HMON, NCEP Global Model (GFS), UKMET (U.K. Met Office), NOGAPS (U.S. Navy), ECMWF (European)

- These models have forecast errors due to...
  - sparse observations
  - inadequate resolution (need to go down to a few km grid spacing; the HMON and HWRF, our highest-resolution operational hurricane models, are currently about 2 km).
  - incomplete understanding and simulation of basic physics of intensity change.
  - problems with representation of shear.

- Steady improvements over past few years to due improved resolution, physics and data assimilation
Consensus and Ensemble Forecasts

• ICON – Consensus that is computed by averaging the forecast intensities from Decay-SHIPS, LGEM, HWRF, and GFDL. All must be available.

• IVCN – Consensus that requires at least 2 of Decay-SHIPS, LGEM, HWRF, and COAMPS-TC.

• FSSE (Florida State Superensemble) – Consensus that uses dynamical models and the previous NHC forecast. The FSSE learns from past performances of its member models in a “training phase”, then accounts for the model biases.

• HCCA (HFIP Corrected Consensus Approach) – FSSE approach adapted to NHC operations
2017 Intensity Guidance

Official forecasts skillful at all times, but were beat by the consensus models at most time periods.

FSSE best model from 24 to 72 h.

HWFI was a strong performer, best individual model.

HMNI not as good as HWFI, but beat statistical aids.

DSHP and HREM were fair performers, but not as good as HWFI, HMNI, and consensus models.

CTCI showed increased skill with time. Strong performer from days 3 to 5.

GFS had some skill, but not competitive. EMXI not skillful.
Atlantic Intensity Error Trends

Errors increased at most time periods in 2017. Long term trends show slow improvement in intensity forecasts.
Based on statistical guidance from SHIPS and D-SHIFOR, qualitative guidance from dynamical models and consensus.

- Dynamical models (HWRF and COTC) more skillful last few years
- Persistence is used quite a bit!
- Obvious signs in the environment, i.e. cooler waters, increasing upper-level winds, are taken into account.
- Generally corresponds to what is *normal* for a storm in any particular situation (e.g. the standard Dvorak development rate).
- Tends to be conservative; *extreme events are almost never forecast*.

For forecasts 24 h and beyond, the average error is roughly 1 SSHWS Category (15-20 knots).
NHC Official Intensity Forecast Trends

NHC Official Average Intensity Errors
Atlantic Basin Tropical Storms and Hurricanes

Intensity error (kt)

Forecast period (h)

1970-79, 80-89, 90-99
2000-09
2010-16
2017
Preliminary
Concluding Remarks

• Intensity forecasting is not as advanced as track forecasting.

• There is less skill for intensity forecasting than there is for track forecasting.

• Current guidance is provided mainly by HWRF, DSHIPS, LGEM, IVCN and more recently, COAMPS-TC, HMON, FSSE and HCCA.

• We still have significant difficulty in forecasting rapidly intensifying and rapidly weakening storms.

• The main hope for the future lies in improved dynamical models, coupled with enhanced observations and understanding of the hurricane’s inner core.

Hurricane Forecast Improvement Project (HFIP)

• GOES-16 is providing new imagery and lightning data for dynamical and statistical-dynamical intensity models.
GOES-16 Imagery and Lightning Locations
EXERCISE 2
Intensity
Forecast